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Flicker Discomfort in Relation to the Lighting of Buildings

By J. B. COLLINS, B.Sc.(Eng.), A.M.I.E.E., *(Member)*, and R. G. HOPKINSON, B.Sc.(Eng.), Ph.D., M.I.E.E., *(Fellow)*.

Summary

An experimental investigation of discomfort due to flicker in lighting installations has been conducted. Most of the experiments were on a full scale with the whole field of view undergoing fluctuation of illumination. The work has shown that the flicker problem in well-engineered installations is not a serious one, and only affects a small proportion of the population. Wide variations in flicker sensitivity have been found, and it has been established that small differences in frequency produce large differences in flicker sensation. Flicker may be more readily perceived in a large area of moderate luminance, for example a white drawing board, than in a small area of high luminance, for example a bare fluorescent lamp. Apart from obviously faulty auxiliaries or lamps, the most likely cause of flicker in fluorescent discharge lamp installations fed from a 50-cycle A.C. supply is the presence of a 50-cycle component superimposed on the normal 100-cycle wave-form.

(1) Introduction

The extensive use of discharge lamps during recent years has drawn attention to the problem of discomfort due to flicker from a fluctuating light source. Two problems exist—(a) that associated with the stroboscopic effect which is experienced when moving parts are viewed under a discontinuous light source of regular intermittency, and (b) that of the perception of flicker, either in the light source itself or in the lighted environment. This paper is concerned with the problem of discomfort due to the presence of visible flicker.

The problem was investigated because the Building Research Board recommended that researches into the possible physiological effects of fluorescent lighting should be accelerated. A review was therefore made of the possible reasons why fluorescent lighting might be thought to be less suitable for general lighting than is filament lighting. Of four causes suggested, namely (a) glare, (b) flicker, (c) emission of ultra-violet light, and (d) unsatisfactory colour rendering, the problem of flicker alone did not appear to have been thoroughly investigated under conditions common in modern lighting practice. Little or no work had been done on flicker perception when the whole field of view was intermittently illuminated. A study was therefore undertaken in which a very large flickering field was used, covering the whole field of view. Such a method of study was different from that used in previous work, but in order to present a general picture of the whole problem, other cognate researches have been drawn upon where the results are considered relevant.

(2) Synopsis of the Investigation

The object of the study was to find why complaints of discomfort from flicker were so numerous, in view of the generally accepted opinion that the frequency of the light fluctuation of a discharge lamp is well above that perceptible to the human eye. In the first experiments, the variability in flicker sensitivity of different subjects on different occasions, and the effect of frequency on sensations of flicker discomfort and the sensation of just perceptible flicker were studied. The results of these experiments

Mr. Collins and Dr. Hopkinson are with the Department of Scientific and Industrial Research at the Building Research Station, Watford, England. The manuscript of this paper was first received on January 14, 1954, and in revised form on February 15, 1954.

indicated that the variability between different subjects on different occasions when viewing large flickering fields was much greater than had been supposed from other studies using small fields. This variability was sufficiently great to indicate the importance of studying the effects of various characteristics of the fluctuating light source on the sensation of flicker produced. From this study it was hoped to assess the probable degree of complaint, or frequency of noticeability, that might be expected from discharge lamp installations under various practical conditions.

The essential variables are the field size, the luminance of the field and the wave-form of the light-time characteristic of the light source, including the modulation characteristic and the dark-time ratio. All these factors had already been investigated by other workers, but it was necessary to carry out an investigation under a limited series of conditions to see how the existing researches could be applied to the present problem or, if they could not be so applied, to study anew the interaction of these variables. The studies were made with strictly practical applications in mind. The study of modulation and its effect on flicker discomfort was related directly to the fact that discharge lamps with luminescent powder coatings possess more or less "afterglow" according to the type of luminescent material used. Light-time characteristics of a large number of fluorescent lamps were obtained in order that the study should be related to practical modulation characteristics. Some use was made of the work of Eastman and Campbell[1] whose proposal to relate the sensation of flicker perception to a flicker index was found relevant to the present work.

(3) Experimental Conditions

(3.1) The Perception of Flicker

During the experiments the subject was asked not only to state when flicker could just be perceived, but also when certain levels of flicker discomfort determined by prior descriptions were experienced. The multiple criterion technique of subjective judgment was employed[2], the physical variable in this work being the frequency of variation of light. By varying the frequency of the fluctuation of light it was possible to change the sensation of flicker received by the subject from that of imperceptible flicker to that of intolerably uncomfortable. Four criteria of judgment were employed:—

(i) Just perceptible flicker;
(ii) Just obvious flicker;
(iii) Just uncomfortable flicker;
(iv) Just intolerable flicker.

The multiple criterion technique so applied to the flicker problem enabled the sensation of flicker to be related to the magnitude of the physical variable, which in this case was the flicker frequency. It is important to note that the multiple criterion method does *not* provide a measure of sensation, but it does indicate the kind of variations in sensation which are produced by changes in the physical factors; it also indicates variance existing between subjects, or between the same subject on different occasions, in terms of their assessment of the sensation.

The measurement of the critical flicker frequency, i.e., the point at which the flashing light stimulus appears to be no longer flickering but shining steadily without interruption, has long been of considerable interest in clinical work and in experimental work on vision. The dependence of this frequency, known as the critical fusion frequency or C.F.F., on such factors as luminance (brightness) was discussed by Porter[3] and by Lythgoe and Tansley[4]. The effects of the amount of area of the retina stimulated intermittently and the amount of modulation of the fluctuating light source have been more recently studied by Bouma[5, 6], while Eastman and Campbell[1] have investigated the effects of more complicated wave-forms and have proposed a "Flicker Index" to express the potential of a wave-form to give rise to perceptible

flicker. None of these studies has, however, investigated the effect of increasing the field size up to the whole of the visual field in order to correspond to the stimulus received from an interior illuminated by intermittent light sources. It also appears that, apart from observations published by Engstrom[7] no attempt has been made to relate sensation in degree to the physical characteristics of the flickering light source.

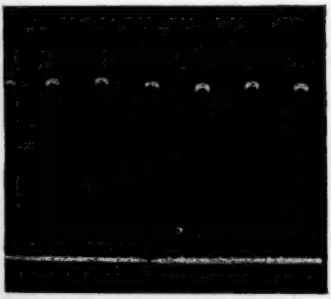
(3.2) Model Study

The first studies were made on a model scale. This experiment was designed to enable measurements to be made of the consistency of each subject's observations and of the variation between different subjects when viewing a large visual field similar to that experienced in common lighting practice. A white card screen was illuminated by filament lamps operating on D.C. A slit measuring 20 cm. × 0.5 cm. in the white card screen was illuminated from behind by another filament lamp also operating on D.C. The observer therefore saw what appeared to be a linear lamp of the same apparent dimensions as a typical fluorescent discharge lamp seen at a distance of 15 ft., surrounded by an area having an approximately uniform luminance of 50 ft.-lamberts.

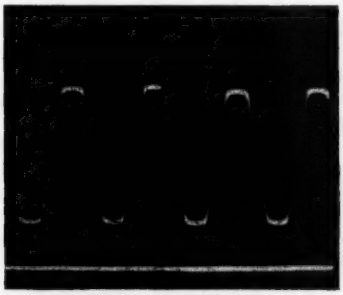
The whole field of view was made to flicker by means of a rotating sector disc placed immediately in front of the subject's eyes and behind the viewing aperture; the disc was driven by a small electric motor whose speed was controlled by the subject himself. By varying the speed of the sector disc the subject could change the sensation of flicker which he received.

(3.3) Full-scale Experiments

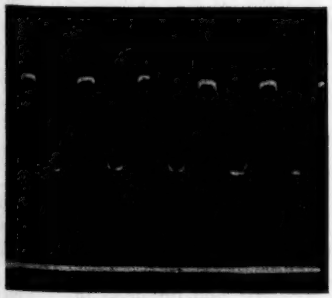
After completing an extensive series of measurements on the model apparatus (the results of which will be described later), the work was repeated on a full scale. A room



100 per cent. modulation.



75 per cent. modulation.



50 per cent. modulation.

Fig. 1. Wave-form of light fluctuation from mechanical flicker source.

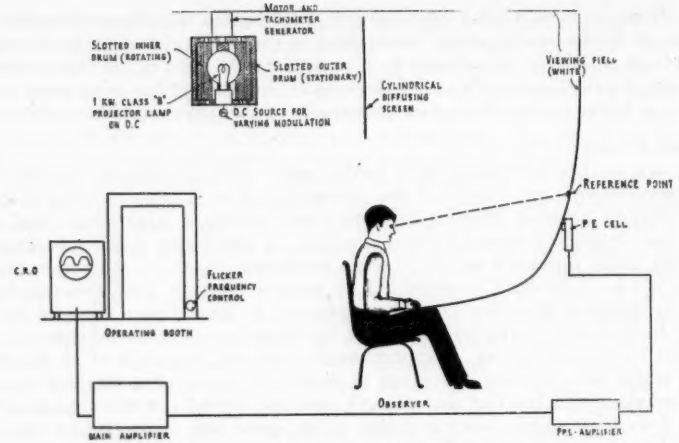


Fig. 2. Experimental arrangement for flicker observation.

of about 80 sq. ft. area, corresponding to a small office, was used for this study. A special lighting fitting was designed consisting of two slotted drums, one of which was stationary and the other rotating, inside which was a 1 kw. Class B projector lamp running on D.C. A large cylinder of diffusing polythene-film surrounded the whole unit so that the appearance of the fitting to an observer entering the room was not particularly unusual; this diffuser also helped to ensure that the illumination on the walls of the room was uniform. The frequency of the intermittency of the light source was governed by the speed of the rotating drum which was measured by means of a tachometer generator connected to a rectifier volt-meter. The light wave-form could be varied if necessary by changing the spacing and the shape of the slots, and it was originally intended that this should be done; in fact it remained constant throughout the experiment and was of the form shown in Fig. 1. The modulation of the wave-form could be varied from 100 per cent. down to 10 per cent. by illuminating the room with additional light from a steady source.

The subject sat in the middle of the room under the lighting fitting which was not visible to him while he was making the observations. He faced a screen covering the end wall of the room which was free from visual distractions and constructed so that the whole visual field was at approximately the same luminance. Two marks on the end wall at his eye level and 5 deg. to his left and 5 deg. to his right, gave him a reference (but not a fixation) point. He was asked to allow his gaze to wander naturally between these two points but not outside them. Behind a translucent screen in the end wall was placed the photocell of a photometer which measured both the amount of light and also the light-time characteristic. (See Fig. 2.)

(4) The Variability of Flicker Sensation

(4.1) The Effect of Variation of Frequency on Flicker Sensation—Observer Variance

A series of observations was made by a number of subjects under fixed conditions of luminance of the field and wave-form of the light source.

The subject, who had been adapted to normal brightness levels of photopic vision, was then given two minutes to adapt to the brightness level of the experiment which was 50 ft.-lamberts (approx.) for the model experiment and 5 ft.-lamberts for the full-scale experiment.

The subject observed the illuminated field binocularly and obtained the required

degree of flicker sensation by adjusting the speed of the sector disc in the model experiment. In the full-scale experiments the speed of the rotating drum was adjusted for him by an experimenter. The frequency of the light source was reduced gradually from a point at which the luminance was fluctuating at a very high frequency (well beyond any possible level of the C.F.F.) to the point at which the flickering became "just perceptible" in some part of the visual field. The frequency was again reduced and the value noted at the point where flicker became "just obvious." The next criterion was "just uncomfortable" at which the flicker, now definitely obvious, was becoming a source of discomfort. Finally the frequency was noted at which this flicker discomfort became "just intolerable."

The subject did not fixate on one point in the field of view. While it is realised that with a small flickering field it is important that the field should be kept on a

Table 1

Results of Observations of Flicker Sensation Made by 20 Subjects

	Criterion	Mean frequency for each criterion			Range of variation of subjects			Separation between each criterion and that following (log units)		
		Cycles/ sec.	Stnd. Dev.	Coefficient of Variation	Av. Range	Smallest Range	Largest Range	Av. Value	Smallest Value	Largest Value
	Column 1	2	3	4	5	6	7	8	9	10
Model Scale Experiment (50 ft.-L.)				Per cent.	Per cent.	Per cent.	Per cent.			
	A Just perceptible	75.1	5.6	7.4	19.4	8	42	.054	.013	.10
	B Just obvious	66.4	8.5	12.8	15	5	25	.057	.034	.11
	C Just uncomfortable	58.2	6.1	10.5	15	7	25	.064	.028	.165
	D Just intolerable	50.3	8.5	16.9	24	6	50			
All-round Visual Field Experiment (5 ft.-L.)										
	A Just perceptible	70.1	4.6	7	12.1	2.6	59.6	.033	.012	.079
	B Just obvious	64.8	5.2	8	8.7	2.8	23.0	.028	.011	.055
	C Just uncomfortable	60.9	5.7	9.3	9.4	4.5	18.2	.037	.013	.068
	D Just intolerable	55.9	6.5	11.7	9.2	3.1	20.5			

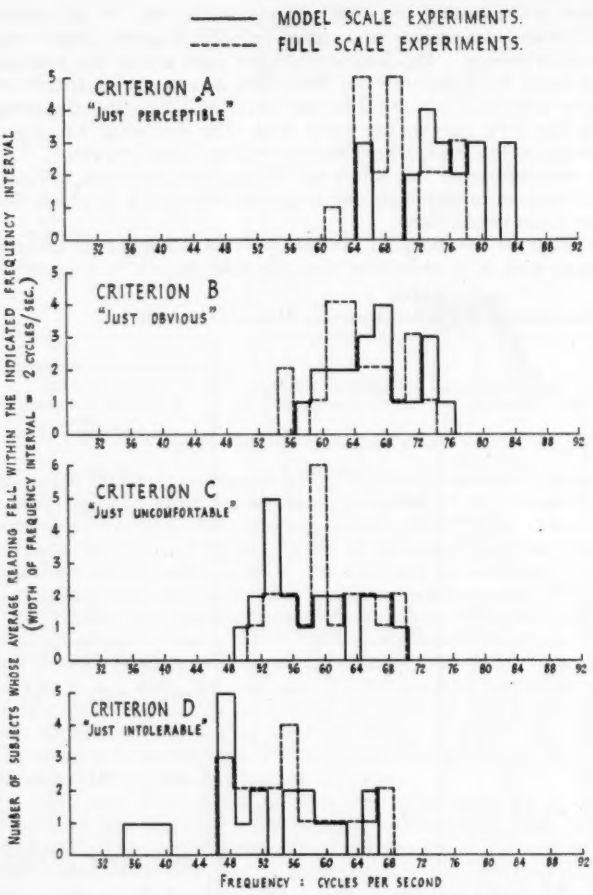


Fig. 3. Distribution of average values of flicker frequency for twenty subjects for four criteria of flicker sensation.

known region of the retina, with a large field and with conditions intended to simulate deliberately an illuminated environment, it was felt wiser that the eye should be allowed to explore the field in the way in which one naturally views or scans the scene when reading, drawing or typing for example. Under such practical conditions the subject will be expected to perceive flicker more readily than if he was fixating. Le Grand[8] describes how, with a peripheral field, if the eye is kept fixed the flicker can disappear after a short time, only to reappear immediately the eye makes the slightest movement.

Observations were made by twenty different subjects chosen at random from the whole staff. Each subject made at least six observations and some made more.

The results of both experiments are shown in Table 1 and in Fig. 3. In the model experiments the maximum variation in just perceptible flicker frequency for all subjects on all occasions was from 56 cycles per second to 120 cycles per second, with a mean value for all the twenty subjects on all occasions of 75 cycles per second. With the

full-scale experiment the corresponding extremes were 57 cycles per second and 107 cycles per second, with a mean value of 70 cycles per second.

A typical variation for any one subject on a number of occasions is illustrated by Fig. 4.

Fig. 3 shows the mean values obtained by each subject plotted in histogram form. The distribution of the twenty individual means is far from being a normal distribution, but if the standard deviation is calculated in the usual way for a normal distribution, it is found to be 5.6 cycles per second (coefficient of variation 7.4 per cent.) in the model experiment, and 4.6 cycles per second (coefficient of variation 7.0 per cent.) in the full-scale experiment. The difference between the model experiment and the full-scale experiment, as far as the " just perceptible " criterion is concerned, is represented by the change in average frequency from 75 to 70 cycles per second, with only a small change in the coefficient of variation.

The frequency changes which correspond to each step of flicker sensation are given in Column 8 of Table 1, and the range in Columns 9 and 10. It will be seen that the average step in frequency corresponding to a change in sensation from one of the chosen criteria to the next is of the order of 8-9 cycles per second (that is, approximately 15 per cent. or 0.06 log units) in the model scale experiments. For the full-scale experiments the average step was only 4-5 cycles per second (that is 8 per

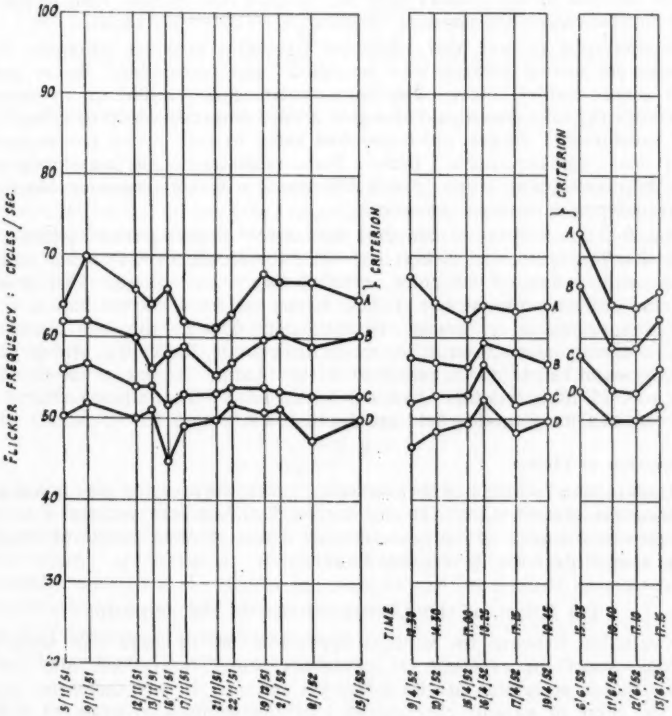


Fig. 4. Variation of one subject on control experiment.

cent. or 0.033 log units), or only a little over one half the average step found in the model scale experiments.

The data at present available do not indicate for certain the cause of the more critical effects of frequency sensation in the full-scale experiment. The most probable conclusion is that the difference is due to the greater field size in the full-scale experiment.

Of the factors contributing to variability in critical fusion frequency, that of visual fatigue has been recently discussed by Zaccaria and Bitterman[10] and by Ryan, Bitterman and Cottrell[11]. Only once in the present investigation was it possible to associate change in fusion frequency with visual work. The factor of age has been discussed by Misiak[12]. The subjects in the present studies were all chosen from the 20 to 40 age group and under the conditions of his experiments Misiak showed that the variation between the limits of this group was only 5-8 per cent., so that the present experiments could not be expected to show any significant variations with age.

Perhaps the most interesting feature of these results is the relatively small change in frequency which is required to produce a large change in flicker sensation. There is, for example, under the full-scale conditions a difference of only 14 cycles per second (that is, between 70 cycles per second and 56 cycles per second) between "just perceptible" flicker and "just intolerable" flicker. This result is relevant in many ways to the lighting problem and may explain, for example, why more complaints of flicker are received in this country with its 50 cycle A.C. supply, than in the United States of America where the standard frequency is 60 cycles per second.

It is interesting to note that Engstrom[7] found a constant difference of about 10-15 cycles per second between what he called "just perceptible" flicker and "disagreeably objectionable" flicker. Engstrom confirmed this difference in experiments with a cathode ray tube screen, and also gave a third sensation which he called "noticeable but satisfactory" flicker which required three to four cycles per second lower frequency than "just perceptible" flicker. These values are of the same order as those found in the present experiment. Small differences in flicker frequency can thus produce large differences in flicker sensation.

During the course of the experiments the subjects, in giving their opinions, usually remarked that they perceived flicker first when the frequency was being reduced, at a point some little way off the point at which they were looking. This observation confirms the general evidence that at these luminance levels the maximum sensitivity of the retina to flicker is between 10 deg. and 30 deg. from the centre of the fovea. It is also of interest that in the model scale study, flicker was always perceived in the background before it was perceived in the "lamp," in spite of the fact that the "lamp" was 45 times brighter than the background. The relative effects of size and luminance of the flickering field are discussed in Section 5.

(4.2) Adaptation to Flicker

An "adaptation" effect has been noted by other workers and was investigated in detail during the present study. It will not be discussed here because it is unlikely that this process will play any appreciable part in accustoming people to installations exhibiting a small degree of perceptible flicker.

(5) Effect of the Characteristics of the Stimulus

The variation between the subjects appears to be so large that some of the observations, under the experimental conditions chosen, may come into the range of possible flicker perception at 100 cycles per second. It was, therefore, necessary to study the effect of various characteristics of the stimulus in order to relate the findings to lighting installations using practical light sources.

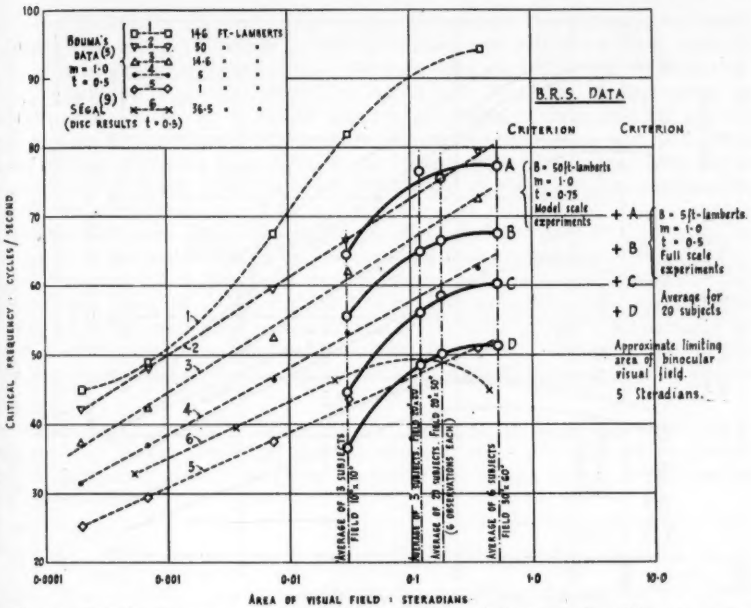

CRITICAL FREQUENCY - CYCLES/SECOND
AREA OF VISUAL FIELD - STERADIANS
BOUMA'S DATA(5) m = 1·0 t = 0·5
SEGAL(9) (DISC RESULTS t = 0·5)
146 FT-LAMBERTS
50
14·6
5
1
36·5
B.R.S. DATA
CRITERION
CRITERION
B = 50ft-lamberts m = 1·0 t = 0·75 Model scale experiments
+ A
+ B
+ C
+ D
B = 5ft-lamberts. m = 1·0 t = 0·5 Full scale experiments
Average for 20 subjects
Approximate limiting area of binocular visual field. 5 Steradians.
AVERAGE OF 3 SUBJECTS FIELD 10° × 10°
AVERAGE OF 5 SUBJECTS FIELD 20° × 20°
AVERAGE OF 20 SUBJECTS FIELD 20° × 20° (6 OBSERVATIONS EACH)
AVERAGE OF 6 SUBJECTS FIELD 30° × 60°

Fig. 5. Relation between area of visual field and critical frequency for different average field luminances.

(5.1) Effect of Size of the Visual Field

Relations obtained between the size of the flickering field and the frequency for "just perceptible" flicker or any other sensation will vary with the experimental method. If, for example, the surrounding field is kept dark, the overall state of light adaptation of the eye will vary with the size of the test field. Lythgoe and Tansley(4) have shown that the sensitivity to a small flickering test field is greatest when the whole surrounding field has the same luminance as the average luminance of the test field, and, therefore, when the state of light adaptation of the eye is the same for all sizes of flickering field. Bouma(5) has published some extensive data on experiments with discs on a black background; these show that under these conditions for luminance levels of one to 50 ft.-lamberts, and areas of the visual field from 0.0002 to 0.35 steradians, the fusion frequency (F) increases with the visual size according to the law :—

$$F = n \log \phi + K$$

$$\text{or } F \propto \phi^{0.087}$$

where ϕ is the solid angle subtended by the visual field at the eye (steradians).

Bouma's results are plotted in Fig. 5, together with some results obtained during the present investigation, to show the trend at large fields of view and the effect on the other criteria of sensation. Bouma's results are in good agreement with the present results, and it was decided to use them to give the relation between frequency for just perceptible flicker and size of the visual field.

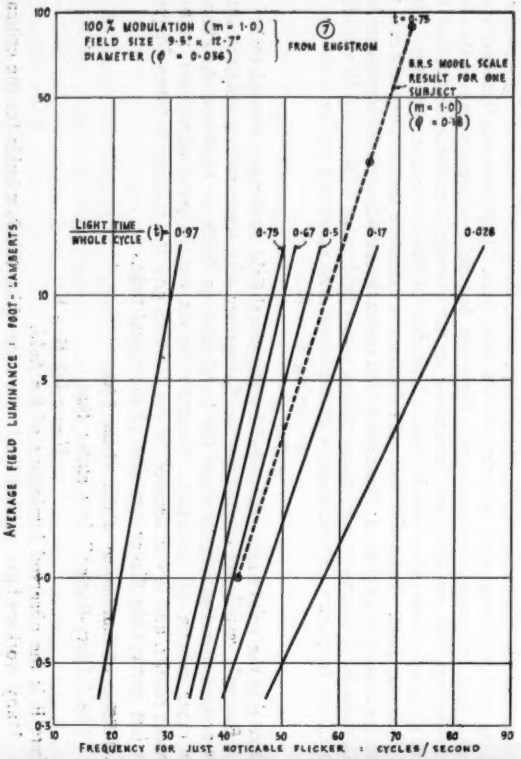
(5.2) Effect of Luminance of the Visual Field

The "Ferry-Porter" law states that

$$F = c \log B + K$$

where B is the observed luminance of the field.

Many workers have studied the limits over which this law holds for the critical or



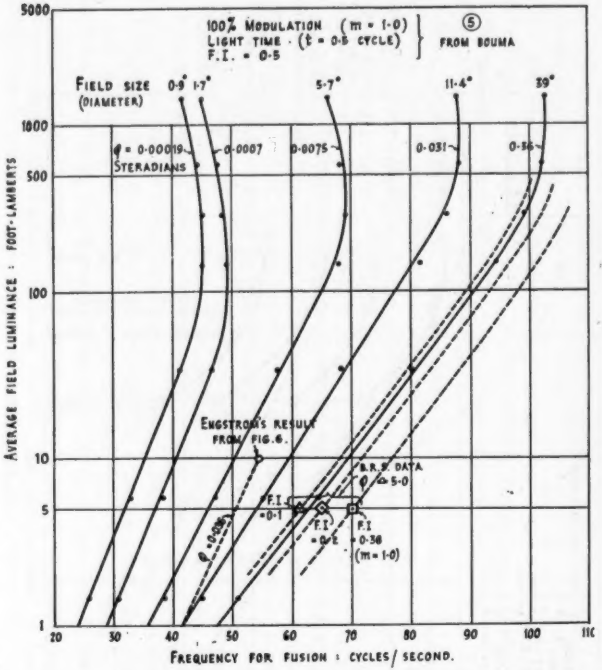


Fig. 6 (left). Relation between average luminance and frequency for 'just noticeable flicker' for different light-time ratios.
Fig. 7 (above). Relation between average brightness and frequency of fusion for different sizes of field of view.

just-perceptible flicker frequency (F). Fig. 6 shows how this relation was found by Engstrom[7] to vary with change in light-time ratio, and includes a check result from the present model scale experiments. Bouma's data plotted in Fig. 7 illustrates the way in which the linear-logarithmic law varies with field size for one given set of wave-form characteristics. It will be seen that according to these data the law breaks down at luminances above 50 ft.-lamberts for small visual fields and at luminances above 300 ft.-lamberts for large visual fields. There appears to be no reason to believe that the law will break down for lower luminances at the maximum possible field of view of five steradians.

Bouma also gives data which enable the effect of the amount of modulation of the wave-form on the above law to be demonstrated for one field size and dark time. It will be seen from Fig. 8 that under the conditions chosen, the law holds for all degrees of modulation from 0.1 to 1.0, and for field luminances of from 0.5 to 50 ft.-lamberts.

The effect of luminance on sensation has not been studied systematically in the present investigation. The relations found by Bouma and Engstrom showed that it could be assumed that the frequency for just perceptible flicker was given by the law:—

$$F \propto B^{0.14}$$

this relation being practically independent of field size or wave-form within the limits given above. It was considered that the above relation was adequate to predict the effect of luminance of the visual field on flicker perception, and so no further studies were undertaken.

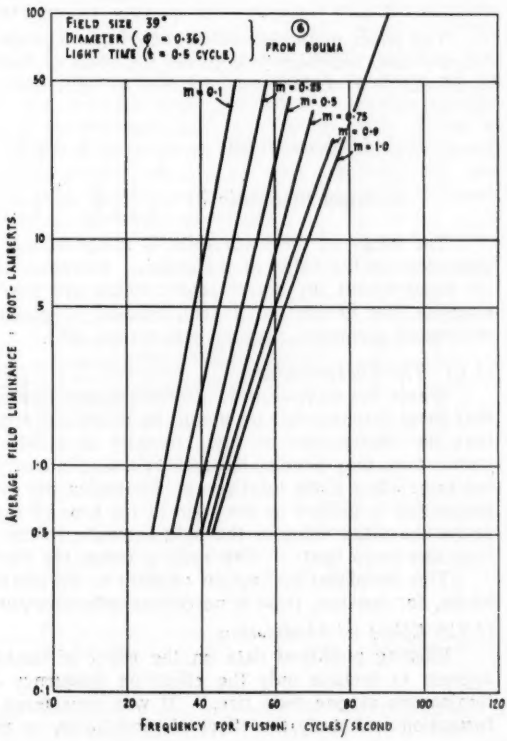


Fig. 8. Relation between average brightness and frequency of fusion for different amounts of modulation

$$'m' = \left(\frac{max. - min.}{max.}\right)$$

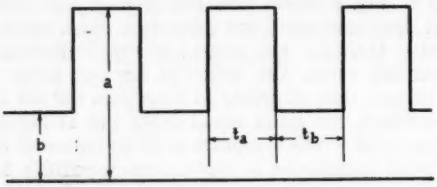


Fig. 9. Rectangular wave form.

(5.3) Effect of Characteristics of the Stimulus Wave-form

The factors affecting the fundamental frequency necessary to produce a given flicker sensation will be, for a rectangular wave-form (see Fig. 9) :—

(i) Minimum amplitude (b) relative to peak amplitude (a)
(ii) Dark time (t_b) relative to light time (t_a)
(iii) Presence of any sub-harmonics or of any lower frequency variation superimposed on the fundamental, as for instance near the ends of a fluorescent lamp.

If $\frac{b}{a} = x$, and $\frac{t_b}{t_a} = y$, it can be shown that the physical average value (B) of the light stimulus is :—

$$\frac{(1 + xy) \cdot a}{(1 + y)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The effect of the absolute level of this average value has already been discussed, but it is also necessary to consider the effect of varying the ratio of minimum to peak amplitude and of dark time relative to light time. These ratios may be expressed as :—

(i) Modulation (m) $= \frac{a - b}{a} \left(= 1 - x \right)$

(ii) Light time ratio (t) $= \frac{t_a}{t_a + t_b} \left(= \frac{1}{1+y} \right)$

The effect of these variables is complex, and the effect of any one is not independent of the value of the others. Moreover they are all dependent to a greater or lesser extent on other factors which are not properties of the wave-form (for example, size of the visual field, method of presenting the stimulus, amount of eye movement permitted, previous adaptation, etc.).

(5.3.1) *The Flicker Index*

Where the wave-form is not rectangular, Eastman and Campbell[1] have proposed that these first two factors should be combined in a single index. On the assumption that the Bunsen-Roscoe law correctly describes the visual effect of intermittent stimulation, they have stated that two time-intensity patterns of stimulation will have the same effect if the total energy fluctuation per cycle is the same. This total energy fluctuation is defined as the ratio of the area of the light-time wave-form curve lying above the mean value of the light ordinate, to the total area of this curve above the base line (zero light). This ratio is called the *Flicker Index.*

This simplified conception appears to be useful for relatively simple wave-forms where, for instance, there is no double inflection during one cycle.

(5.3.2) *Effect of Modulation*

Existing published data on the effect of modulation of the stimulus wave-form appears to include only the effect on frequency of flicker fusion at various field luminances at one field size. It was considered necessary to supplement this information and study the effect of modulation on the four criteria of sensation when

stimulating the whole field of view at values of field luminance giving (a) constant average luminance and (b) constant peak luminance. These results were obtained with the full-scale apparatus by adding appropriate amounts of steady luminance to the fluctuating luminance produced by the drum fitting.

Fig. 10 shows the effect of varying the modulation between 0.1 and 1.0 on the frequency required for each of the four criteria of flicker sensation, expressed in terms of the Flicker Index. These relations are shown for conditions where the average luminance was maintained constant as the modulation was varied, as well as for conditions where the peak luminance was maintained constant. It will be seen that linear-logarithmic relations exist between the Flicker Index and frequency for each sensation level, with the exception of the frequency for " just intolerable " flicker.

The slopes of the curves in Fig. 10 are not very great, indicating the relatively small effect of change of modulation upon the frequency required for a given degree of sensation of flicker. At a given frequency, however, changing Flicker Index by a factor of two can change the sensation by one criterion, for example, from " just uncomfortable " flicker to " just obvious " flicker, or from " just obvious " flicker to " just perceptible " flicker.

The maximum discomfort which could be produced by the flickering stimulus with small amounts of modulation was much less than that with large amounts, and in fact at a modulation of 0.1 it was often not possible to produce great discomfort for certain subjects however low the frequency was reduced.

Bouma's results for the critical fusion frequency are compared with those of the present investigation in Figs. 11 and 12. The effect of increasing the size of the visual field appears to be a reduction in slope of the linear-logarithmic relation; that is, the effect of changing Flicker Index seemed to be less critical, in terms of the frequency for a given level of sensation, with the larger visual field. Bouma's results show that the slope of the relation showed practically no change with change in average luminance, so it was not considered necessary to repeat the present experiments for different field luminances. The general relation between frequency for just perceptible flicker (F) and Flicker Index (I) deduced from these results may be expressed in the form : $F \propto I^{0.11}$ (for fluctuation of the whole visual field).

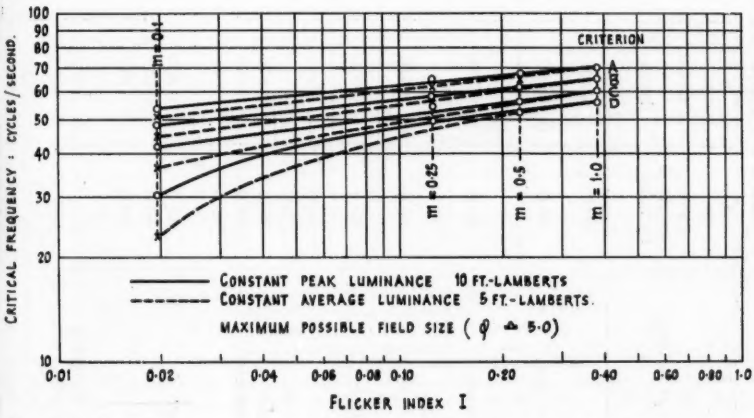


Fig. 10. Relation between flicker index and critical frequency for four criteria of flicker sensation.

Table 2

Wave-Form Characteristics of Discharge, Incandescent and Fluorescent Lamps

1 Type of lamp		2 Power consumed by lamp	3 Current in lamp	4 Mains Voltage	5 Ratio Min : Max	6 Per cent. Flicker $\frac{(\text{Max}-\text{Min})}{(\text{Max}+\text{Min})} \times 100$	7 Ratio Mean : Max	8 Flicker Index	9 Rectification*
		Watts	Amps.	Volts					
Tubular fluorescent	(a)	80.0	0.832	238.0	0.570	27.4	0.810	0.078	—
"Warm" (Pinkish)	(b)	80.0	0.888	240.5	0.460	37.0	0.750	0.110	0.014
Tubular fluorescent	(c)	80.0	0.846	239.0	0.390	44.0	0.740	0.120	—
"Medium"	(d)	80.0	0.870	239.5	0.375	45.5	0.735	0.125	—
	(e)	80.0	0.850	239.5	0.355	47.6	0.725	0.130	0.017
Tubular fluorescent	(f)	80.0	0.816	236.2	0.253	59.7	0.668	0.153	0.033
		64.0	0.620	210	0.285	55.7	0.695	0.144	0.010
		88.0	0.956	250	0.242	61.0	0.648	0.157	0.097
"Cold"	(g)	80.0	0.806	234.5	0.184	68.9	0.668	0.167	0.028
		66.0	0.622	210	0.185	68.7	0.686	0.164	0.012
		89.0	0.942	250	0.174	70.4	0.655	0.173	0.034
200w Tungsten		—	—	230	0.83	8.7	0.91	0.032	—
125w MBF/V		—	—	230	0.114	79.5	0.53	0.269	—
125w MB/V		—	—	230	0.065	87.8	0.50	0.290	—
60w SO/4		—	—	230	0	100	0.58	0.256	—

*Difference in height of adjacent peaks divided by mean height of peaks.

XUM

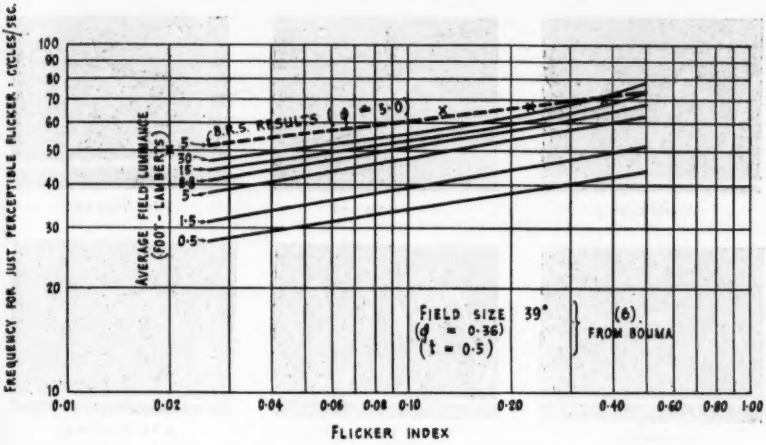


Fig. 11. Relation between flicker index and frequency for just perceptible flicker for different average luminances.

(5.3.3) *Effect of Light-time Ratio*

Engstrom's results(7) on the effect of light-time ratio of the stimulus wave-form on flicker threshold can be expressed in terms of Flicker Index. His results for constant value of modulation and a stimulus of constant average luminance of 5 ft.-lamberts subtending a solid angle of 0.036 steradians at the eye have been plotted in Fig. 12. It seems reasonable to deduce from these results that within certain limits any change in the wave-form of a light stimulus, excepting any introduction of components of frequency lower than the fundamental, will cause a change in logarithm of the threshold frequency proportional to the change in the logarithm of the relevant Flicker Index.

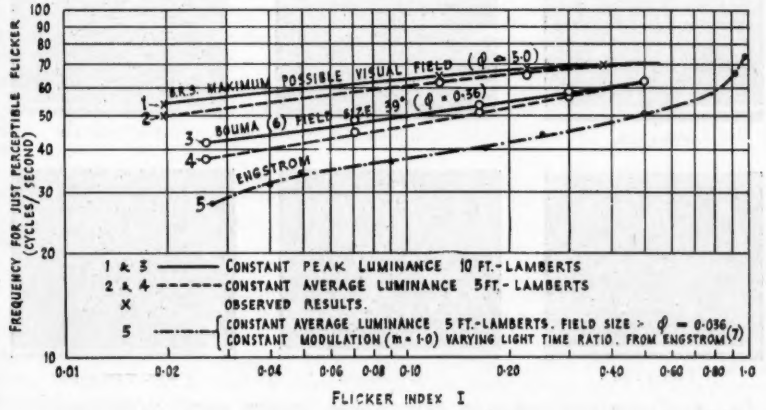

FREQUENCY FOR JUST PERCEPTIBLE FLICKER (CYCLES/SECOND)
B.R.S. MAXIMUM POSSIBLE VISUAL FIELD (ϕ = 5·0)
BOUMA (6) FIELD SIZE 39° (ϕ = 0·36)
ENGSTROM
1 & 3 —— CONSTANT PEAK LUMINANCE 10 FT.-LAMBERTS
2 & 4 ------ CONSTANT AVERAGE LUMINANCE 5 FT.-LAMBERTS
X OBSERVED RESULTS.
5 CONSTANT AVERAGE LUMINANCE 5 FT.-LAMBERTS. FIELD SIZE > ϕ = 0·036
CONSTANT MODULATION (m = 1·0) VARYING LIGHT TIME RATIO. FROM ENGSTROM(7)
FLICKER INDEX I

Fig. 12. Relation between flicker index and frequency for just perceptible flicker.

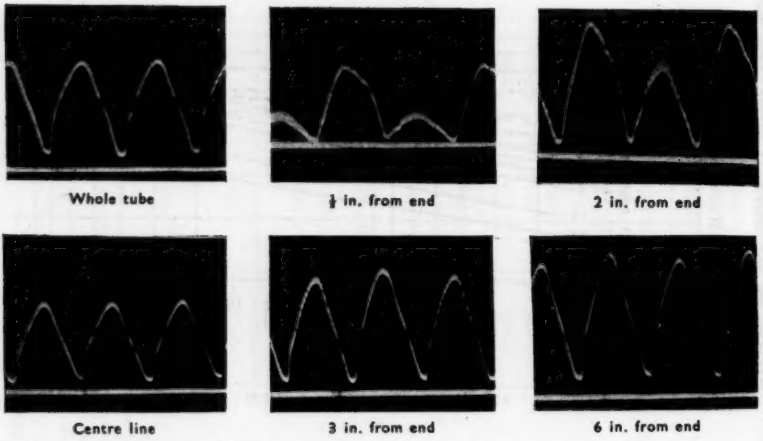


Fig. 13. Typical wave-form traces for an 80-watt "cold" colour fluorescent lamp (choke ballast)

(6) The Fluctuation of Practical Light Sources

(6.1) The Wave-form of Light-time Function of Discharge Lamps

Photometric apparatus was set up to examine the wave-form of different types of discharge lamp. This apparatus consisted basically of an electron multiplier type photo-electric cell whose output was fed through an amplifier to a double-beam oscillograph. A filter was used to bring the spectral response of the cell to correspond as far as possible with that of the standard eye. The linearity of the oscillograph deflection, and its independence of frequency over the ranges involved, were checked

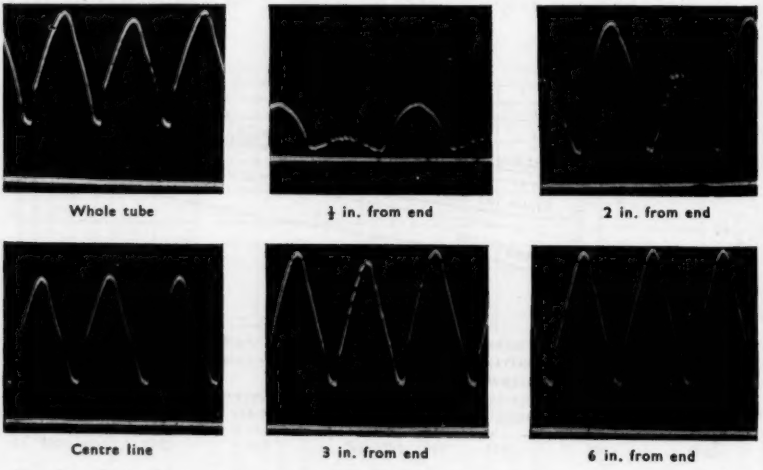


Fig. 14. Typical wave-form traces for an 80-watt "medium warm" colour fluorescent lamp (choke ballast)

Table 3

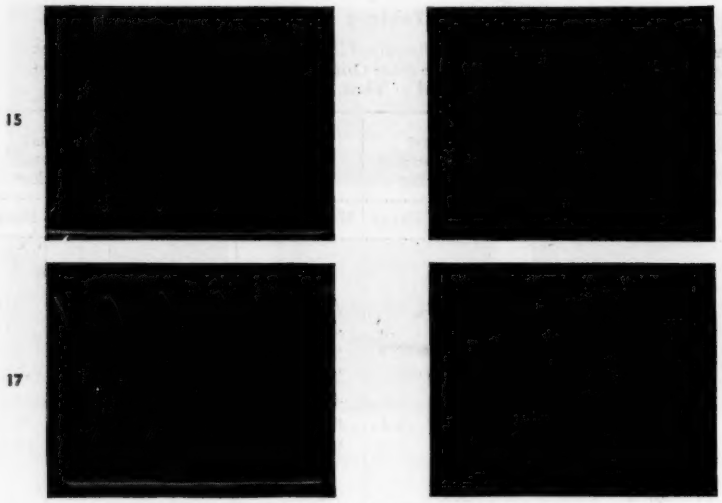
Percentage of 50 cycle Component Required in the Wave-Form of Light Output From a Fluorescent Lamp to Produce Four Criteria of Flicker Sensation. Average Luminance of Whole Field of View 40, 10 and 4 ft.-lamberts

Field luminance	Subject No.	No. of observations from each subject	Just perceptible flicker		Just obvious flicker		Just uncomfortable flicker		Just intolerable flicker	
			Mean	Range	Mean	Range	Mean	Range	Mean	Range
ft.-L										
40	7	6	All < 1.0		All < 2.5		3.2	2.3	5.0	3.0
	1	11	1.2	1.6	4.0	3.9	7.4	6.2	14.5	9.9
	2	10	4.3	3.7	9.6	4.5	14.5	3.7	20.6	3.3
	3	6	2.4	2.5	7.4	2.4	13.5	5.5	23.1	5.7
	4	6	1.7	0.7	4.8	4.7	12.7	4.3	20.6	11.3
	5	9	2.2	3.4	8.0	8.1	16.1	6.0	25.7	13.5
	6	11	3.3	2.3	9.2	5.3	19.5	17.9	29.1	14.7
	Average of 6 Subjects		2.5		7.2		14.0		22.3	
10	Average of 6 Subjects	6	15.5		38		65.9		>108	
4	Average of 3 Subjects (1, 5, and 6)	6	35.7		74.8		143 or over		>170	

experimentally. The wave-form traces of the integrated light output of the lamps were photographed and printed on to dimensionally stable metal foil interleaved paper. The various characteristics of the wave-form were measured from these prints. A selection of the 5 ft. 80-watt fluorescent lamps used were sent to the National Physical Laboratory for confirmation of the measurements and their results are given in Table 2. This Table also gives the results of measurements obtained by the authors on other discharge lamps where the arc is the sole, or the main source of luminous output. Measurements on a 200-watt tungsten filament lamp are included for comparison.

It will be seen from Table 2 that the value of Flicker Index for the wave-form varies from 0.08 for tubular fluorescent lamps coated with long after-glow powder giving a "warm pinkish" light, to nearly 0.17 for lamps with short after-glow powder giving a "cold bluish" light. The typical wave-form traces are shown in Fig. 13 and 14. The extent to which the wave-form varies with the voltage applied to the lamp has been investigated, and results for one type of lamp are shown in the Table.

Table 2 indicates that, as would be expected, the fluctuations of light output from discharge lamps where the arc is the main source are much more severe than those of the light output of fluorescent lamps where the main light source is the powder coating. Figs. 15, 16, 17 and 18 show typical wave-form traces for 125-watt mercury luminescent, plain 125-watt mercury, 60-watt sodium, and 200-watt tungsten filament lamps respectively.



Light output wave-forms of discharge and incandescent lamps.

Fig. 15. 125-watt MBF/V mercury discharge lamp.
Fig. 16. 125-watt MB/V mercury discharge lamp.
Fig. 17. 60-watt SO/H sodium discharge lamp.
Fig. 18. 200-watt 230-volt filament lamp.

(6.2) The Effect of the Presence of Sub-harmonics

A discharge lamp which behaves with electrical symmetry will exhibit a light periodicity of 100 cycles per second when connected to a 50 cycle A.C. supply. Close to the electrodes, however, certain portions of the discharge path will be bright or dark according to whether the electrode is the anode or the cathode at any given instant. The effect of this on the light output of that part of the source can be considered as producing a large 50-cycle component superimposed on the 100-cycle fundamental, as shown in Fig. 13. In a hot-cathode fluorescent lamp, this 50-cycle component occurs over a sufficient area and at a sufficiently high average luminance to produce very frequently a sensation of flicker either when the tube is looked at directly, or when it illuminates an area close to the end of the tube to a high luminance (for example, parts of fittings, ceilings, etc.). The usual practice of screening two inches at each end of the lamp is generally sufficient to eliminate any appearance of flicker.

It was noticed, however, during the measurements on a number of fluorescent lamps that occasionally the 50-cycle component associated with one of the electrodes persisted along most of the length of the lamp. The wave-form of the total light output was then of the form shown in Fig. 14, where it will be seen that the lamp as a whole is emitting more light on one half of the cycle than on the other. This is said to be due to a slight difference between the emission of the two electrodes, and might be expected to be a concomitant of the ageing of the lamp through its life. The effect does, however, occasionally appear in a new lamp. The exact nature and extent of the differences between the two electrodes to cause this effect are not known. It is intended to study what proportion of lamps in any given large sample of new or old lamps show the effect.

The effect of such sub-harmonics on the sensation of flicker was investigated. The 50-cycle component was introduced into the wave-form of light output from the

fluorescent lamps by inserting in the circuit a metal rectifier shunted by a variable resistance. The amount of 50-cycle component introduced was defined as the difference in height between adjacent peaks of the light wave-form trace on the oscillograph, divided by the average height of the two peaks, expressed as a percentage. Thus a wave-form with no 50-cycle component had a value of 0 per cent., and a 50-cycle wave-form with no 50-cycle component had a value of 200 per cent. The amounts of 50-cycle component required for the four criteria of sensation when the whole visual field was illuminated to luminance levels of 40, 10, and 4 ft.-lamberts are given in Table 3.

None of the subjects required more than 4.3 per cent. of the 50-cycle component for flicker to become, on the average, "just perceptible" with a field luminance of 40 ft.-lamberts. Some required only just over 1 per cent., the average for the six subjects being 2.5 per cent. The seventh subject was one who in the survey described in Section 4 had shown a high sensitivity to flicker, and it was not surprising to find that at a luminance of 40 ft.-lamberts he could occasionally perceive the 100-cycle flicker without any additional 50-cycle component, and that any amounts of the latter which were required on other occasions were extremely small.

The relations between field luminance and critical percentage of sub-harmonic for each criterion of sensation are given in Fig. 19. For practical purposes an approximately linear relation may be assumed to exist between the logarithms of field luminance and percentage of 50-cycle component over the range examined for all four criteria.

(7) Applications to Lighting Practice

(7.1) Variability of Sensitivity

It has been shown that when the whole visual field is stimulated there is such a wide variation in the sensitivity of different people at different times that some few people may complain of perceptible or even uncomfortable flicker in situations where the majority cannot appreciate any flicker at all. The designer has to choose between an installation whose characteristics are arranged so that no one can see any flicker, and an installation more convenient to design but in which a few people sensitive to flicker may be expected to complain.

(7.2) Possibility of Perceiving 100-cycle Flicker

The results of this and other investigations into the effect of the different variables on flicker perception can be summarised in the following relationship:—

$$F \propto \phi^{0.087} \cdot B^{0.14} \cdot I^{0.11}$$

where F is the critical fusion frequency (cycles per second);

ϕ is the solid angle (steradians) subtended by the flicker field at the eye;

B is the average luminance (foot-lamberts) of the field of view;

I is the Flicker Index of the wave-form.

This formula has a limited usefulness, and is given to enable a general appraisal to be made of the significance of the different variables from the point of view of lighting design. The variables are not, however, independent of one another, so that care should be exercised in its use.

With the aid of the formula, and by deducing a probability function from the standard deviation of all the observations taken in the sensitivity study (Sections 3 and 4), the degree of probability of flicker perception at a given luminance can be inferred. Three typical conditions met with in practice will be considered—(a) that of lamps where the arc is the main source of light (Flicker Index = 0.3), (b) lamps with a Flicker Index of 0.2 (typical "cold" fluorescent lamps have a Flicker Index of the order of 0.16), and (c) lamps with a Flicker Index of the order of 0.1 (such as some "warm" fluorescent lamps).

Flicker at 100-cycles from a lamp of Flicker Index 0.3 will be noticed on 50 per

cent. of all observer-occasions if the field luminance is of the order of 100 ft.-lamberts. If the luminance is 50 ft.-lamberts, flicker will be perceived on one observer-occasion in 14. If the luminance is 10 ft.-lamberts the possibility of flicker being perceived is remote.

With a Flicker Index of 0.2, flicker will be perceived on 50 per cent. of all observer-occasions if the luminance of the whole field is of the order of 200 ft.-lamberts. At a luminance of 50 ft.-lamberts, flicker will be perceived on one observer-occasion in 33, and at a luminance of 10 ft.-lamberts the possibility of flicker perception is very remote.

With a Flicker Index of 0.1, flicker will be perceived on 50 per cent. of all observer-occasions at a field luminance of the order of 450 ft.-lamberts. If the luminance is 50 ft.-lamberts, flicker will be perceived on one occasion in 150; the possibility of its being perceived at 10 ft.-lamberts is very remote.

These deductions show that in a well-designed lighting installation normal people are unlikely to complain of flicker.

Assumptions are made in the above deductions which are believed to be justified although they have not all been checked experimentally.

Light fluctuations at flicker frequency of 100 cycles per second will not be perceived by the "average" observer under practical conditions unless the luminance of the field is high as, for example, with luminous ceilings. Here, however, it would be considered good lighting practice to screen the surface at intervals to avoid large areas being seen in the normal field of view. The luminance of a well-lighted drawing board is of the order at which flicker will be perceived on many occasions by people within the normal distribution. It is, therefore, of interest that most of the complaints of fluorescent lighting have come from people who work on drawing-boards or with high luminance areas in their field of view.

(7·3) Possibility of Perceiving 50-cycle Flicker (Sub-harmonic)

The 50-cycle sub-harmonic is perhaps the most likely cause of complaints of flicker after such obvious faults as end flicker, faulty starters, and poor lamps have been remedied. At luminances of 40 ft.-lamberts over the whole field of view, the

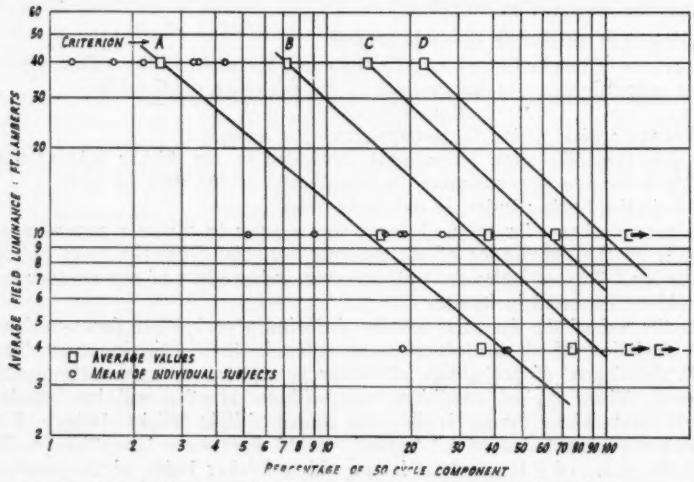


Fig. 19. Relation between field luminance and percentage of 50-cycle component superimposed on 100-cycle wave-form for four criteria of flicker sensation.

amount of 50-cycle component detectable by the average person is about 2½ per cent., which is not uncommon in practice. The most important requirement at this stage is to discover to what extent fluorescent lamps show this characteristic at various stages of their life and to consider whether steps can be taken to reduce the likelihood of it occurring. Part of the importance of 50-cycle component results from the fact that combining the lamp with one or two other normal lamps supplied with current at different phase angles does not eliminate the 50-cycle component, but only reduces its amplitude relative to the average light output of the combination.

(7·4) Reduction of Flicker

The influence of luminance and area pattern of the visual field on flicker perception has already been discussed with reference to drawing-boards and luminous ceilings. The other factor which is to some extent under control is the light wave-form characteristic of the lamp or group of lamps.

The effect of the fluorescent powder used in a discharge lamp on Flicker Index and hence on the possibility of flicker discomfort can be appreciable. Choice of powder may be considered as a means of reducing complaints about flicker and stroboscopic effects. In the sample of lamps measured the " warmer " coloured lamps had a much longer after-glow and hence a lower Flicker Index than the " cold, bluish " lamps. It is understood that the amount of after-glow is not necessarily related to colour with the powders now available. Such a choice might, however, conflict with the requirements of good colour-rendering. The lamps with the longest after-glow have a Flicker Index approximately half that of those with the shortest after-glow, and it has been shown that if conditions are such that flicker discomfort occurs, a change of this amount in Flicker Index at a given frequency will change the degree of discomfort by one criterion.

It is common practice to connect adjacent lamps in an installation to different phases of a three-phase A.C. supply, or to alter the phase relation between two adjacent lamps by using a "lead-lag" circuit, in order to reduce the stroboscopic effect or possibility of flicker perception. The best method of increasing the effective frequency of the light output wave-form is, undoubtedly, the former. It is important that the contributions from each of the three lamps to the luminances in the field of view should be equal, and, therefore, it is preferable that the three lamps should be in the same fitting. If this is done, the light emitted will have a wave-form with a fundamental frequency of 300-cycles, any differences in light output between the three lamps will appear as 100-cycle components and any rectification effects in any one of the lamps as a 50-cycle component superimposed on this 300-cycle fundamental. The amount of modulation will be quite small, as shown in Fig. 20, and in general less than that shown by a tungsten filament lamp of 200 watts on a 230-volt A.C. supply (Fig. 18), as well as occurring at three times the frequency.

In view of the complications of connecting a three-phase supply to a single fitting, it is at present more usual to connect adjacent fittings to the different phases. The success of this practice in reducing the possibility of flicker perception or stroboscopic effect will depend on the degree of mixing of the light from the different fittings before it falls on whatever large bright surfaces there are in the field of view, or on the moving objects in question. The amount of 100-cycle component will vary from zero at points where equal luminance is produced by fittings on three different phases, to a maximum value close to one individual fitting.

To avoid the expense of multi-phase wiring it is common practice to feed the lamps in a single two-lamp fitting through different ballasts, one producing a leading current characteristic and one a lagging current characteristic. These circuits, however, are usually constructed to give a high resultant power factor, with minimum power loss in the ballasts, the currents in the two branches being more than 90 deg. out of phase. The effect on the combined light output from the two lamps is shown in

Fig. 21, from which it will be seen that the fundamental frequency of the light-output wave-form is still 100-cycles per second but the modulation has been reduced by the phase displacement. The Flicker Index of this wave-form is 40 per cent. lower than that of the single lamp on the inductive ballast; the effect of this change can be compared to the change which can be effected by changing from lamps with a short afterglow to lamps with a long afterglow, that is, that under conditions causing flicker discomfort, an improvement of one criterion of flicker discomfort may be effected.

A circuit has been proposed in France[13] for operating three lamps through phase splitting gear to achieve a phase difference of 60 deg. between the current in each lamp. The wave-forms of the light output from the three separate lamps and that of the combined light from the three lamps connected in a circuit arrangement of this type is shown in Fig. 22. The frequency of the main component of this wave-form is 100 cycles per second, but the modulation is only 0.27 and the Flicker Index is 0.035.

(8) Conclusions

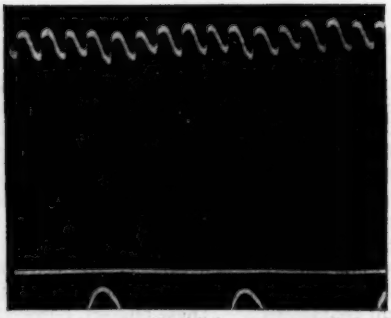
The results of the investigation have shown the great variability in sensitivity to flicker of different subjects on different occasions. This factor, when considered in conjunction with the available and the newly determined data on the factors affecting the potentiality of any type of regular light fluctuation to produce various degrees of flicker sensation, provides an indication of the circumstances under which a lighting installation may give rise to complaints of flicker.

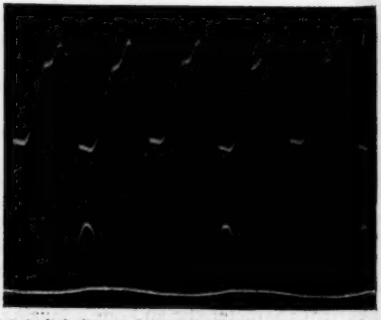
Flicker may be more readily seen in a large area of moderate luminance than in a small area of high luminance.

The effect of the wave-form of light output from the fluctuating light source is complicated but it can be deduced that the effect of the afterglow of commercially available fluorescent lamps in reducing flicker is significant.

Apart from obviously faulty auxiliaries or lamps, the most likely cause of flicker in tubular flourescent lamp installations fed from a 50-cycle A.C. supply is the presence of a 50-cycle component superimposed on the normal 100-cycle wave-form. A small amount of such a component can cause perceptible flicker at low luminances and uncomfortable flicker at higher luminances such as those likely to be met with on drawing-boards.

Multi-phasing is valuable in reducing both the possibility of flicker perception and stroboscopic effect. The "lead-lag" circuit has been shown to have an effect on wave-form of light output which is analogous to increasing the afterglow of a





Combined light output wave-forms of MCF/U "daylight" type fluorescent lamps.

Fig. 20. Three 80-watt lamps fed from three phases of 50-cycle 3-phase supply.

Fig. 21. Two 40-watt lamps in commercial "lead-lag" circuit.

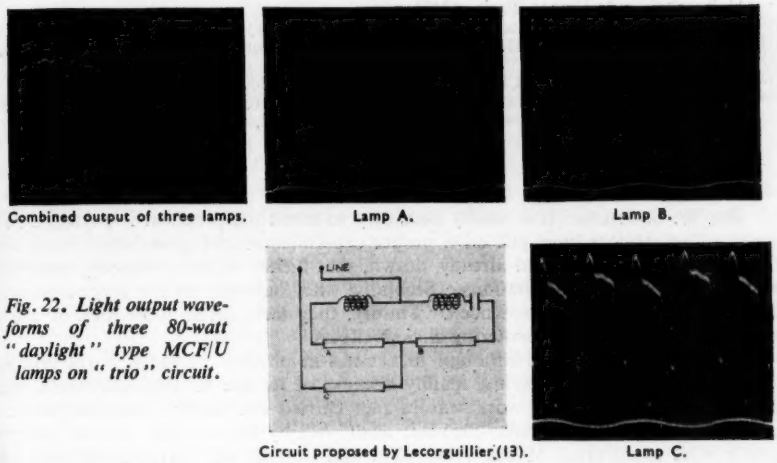


Fig. 22. Light output waveforms of three 80-watt "daylight" type MCF/U lamps on "trio" circuit.

luminescent powder coating. The effect of this circuit as normally used is to reduce the modulation of the normal 100-cycle wave-form rather than to produce a 200-cycle basic wave-form.

Only a few matters on the fringe of this complicated branch of neuro-physiology have been elucidated. More work will need to be done before a complete picture can be obtained of the relation between all the characteristics of a light source and the resultant flicker sensation. On the other hand, the investigation may have served to put the flicker problem in modern lighting in its proper perspective in relation to all the other factors which go to determine what is good lighting. The investigation will have achieved its purpose if it draws attention to the need for sound engineering of discharge lamp installations, and also to the fact that flicker, in a well-designed and maintained installation, is not likely to be a serious lighting problem.

Acknowledgments

The authors thank Dr. Stiles of the National Physical Laboratory and his staff for their help in measuring the wave-forms, and the Director of the National Physical Laboratory for permission to publish the results of these measurements.

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Discussion

DR. W. S. STILES: It is hardly necessary to stress the practical importance of this paper. The authors have put on a proper experimental and quantitative basis a conclusion that most of us had already drawn, that flicker is not commonly experienced in fluorescent lighting installations. Secondly, they have shown the precise conditions under which it will be experienced. Thirdly, they have given some idea of the way to reduce the risk of encountering flicker effects.

It is worth noting that although flicker has in practice played a fairly prominent rôle in illuminating engineering, mainly because of its use in heterochromatic photometry, most of the earlier work was in fact carried out under conditions which are not applicable to the particular problem dealt with by the authors. It was concerned mostly with small areas of the visual field and not the very large areas with which the authors dealt. Another point of difference is that in the past it has been almost exclusively the critical fusion frequency which has attracted attention. The gravity of flicker effects below the critical frequency was not considered. Again the consequences of modifications in wave-form have been little studied.

In 1926 there was, however, an investigation by Hartridge, Lythgoe and Bannister with somewhat similar objects to that of the present investigation. In that work the ability to carry out various tasks under continuous and flickering illumination of the same mean value was examined. Visual acuity, contrast sensitivity, colour sensitivity, speed of reading and several other things were tried out. The general conclusion was that as between continuous and flickering illumination there was no appreciable difference in the ability to do such work.

In those days the question that one asked about a characteristic of lighting was "Does it assist or interfere with your ability to do a particular job?" Of course, nowadays the question runs rather differently—"Are you perfectly comfortable?", "Is the lighting in the least degree irritating?", and so on. One might almost describe this a change to the Welfare State in lighting. It is rather noticeable in the work by Hartridge and his collaborators that they seemed little concerned with whether the observers felt comfortable in doing the tests. They were interested in flicker from a 25-cycle A.C. supply. It appears from the conditions which they used that the flicker experienced by their subjects must have been, on the Collins and Hopkinson scale, rather worse than "just intolerable." Mr. Collins and Dr. Hopkinson make no reference to how well you can perform under various degrees of flicker. They have been solely concerned—and rightly so—with the subjective impressions of flicker. The difficulty of establishing small deleterious effects in vision by performance tests has been amply demonstrated.

I think there will be many others following me who will deal with the practical import for fluorescent lighting of the conclusions that the authors have drawn in the paper. There are, however, quite other aspects of the work regarded as a contribution to our knowledge of flicker phenomena generally.

There is one thing in particular which interested me. We are dealing with very large fields, and the authors have shown that as you get larger fields you get increased flicker sensitivity. On the other hand, they report in their paper that subjects usually observed flicker originally in one particular part of the visual field—between 10 deg.

and 30 deg. away from the direction of view. If that is so then it may be that the effect of the area of the visual field which at that moment is not visibly flickering is really no more than the effect of a surround, which might just as well be a continuous surround as an alternating surround. I should like to have the authors' views whether the part of the field which is not apparently flickering is contributing to the sensation of flicker at the most sensitive region in a different way from what it would be if it were a continuous surround.

In the waveform problem it would have been nice to have had the sub-harmonic contribution to the waveform and the harmonics which determine the shape of the 100-cycle variation handled in a unitary way. They were discussed quite separately in the paper, and they were dealt with in separate experiments. The reason for this is easy to see. In a harmonic analysis with the 50-cycle frequency as fundamental, it is quite clear that most of the "energy" would be in the first harmonic, and that would not lead to a very easy situation in obtaining a formula to cover all the effects in a unitary way. However, I do not feel that the Flicker Index is the last word on this matter. Perhaps the authors could add something on this point.

I come now to the criteria of degrees of flicker. Those of us who have done work on the more ordinary visual thresholds where you have to say "Yes" or "No" —that you can see something or you cannot see something—are always very impressed by the fine distinctions which the observers in an investigation of this kind are able to draw. I mean the precision with which they determine whether they feel a slight obnoxiousness in the lighting or whether they find it just too utterly beastly! It is surprising that they hit off with the precision that they do these higher criteria.

There are, of course, other analyses which have been put forward of the sensations which you get when you drop the frequency below the critical frequency of fusion. Bartley, in America, has given an analysis distinguishing fine and coarse flicker and, with still lower frequencies, glitter.

I believe that something has been done to try to relate these classifications of flicker effects to electro-physiological observations, the fluctuations in the electrical potentials detectable in and around the brain. We have here this evening some physiologists who may be following up that point. I wonder whether the authors have any speculations on whether their criteria could have a correspondence with brain rhythms of the same general kind as the alpha rhythm. One wonders, because the alpha rhythm, the main rhythm that one picks up from the brain, has a frequency of only about 10 cycles per second, which seems very much lower than the whole gamut of unpleasant flicker frequencies which we have been hearing about this evening.

DR. K. TANSLEY: I have been very much interested in this work because I was concerned a long time ago in a certain amount of work with Dr. Lythgoe on fusion frequency and the effect of adaptation.

Under the most favourable conditions which we then employed—we always used a small field, that is with the highest illumination on both test field and surrounds that we could get in those days—we never got a fusion frequency as high as the author's "just perceptible" flicker. We never got one above 50 cycles per second.

When I first started hearing about complaints of 100-cycle flicker I did not believe it. I thought people were imagining things. Even when I heard of the results obtained by Dr. Hopkinson and Mr. Collins, at the beginning I did not believe them. But when I was tested myself on their model scale experiment, I ran straight up to between 70 and 80, and so I had to think again. Presumably the differences are due to the much higher luminance levels and the much bigger visual field.

I want to ask the authors about their individual day-to-day variations. In our experiments we never got anything like such big variations from day to day. We got variations from one individual to another, but our day-to-day variations were

very small. Admittedly we took all possible precautions to make them as small as possible, because we were not interested in variations if they could be avoided. I wondered whether one reason might be the very short pre-adaptation which the subjects were given, i.e., that the explanation might lie in what one might call the past light history of the subjects.

I want now to mention a matter on the neuro-physiological side which has been hinted at. It has now been shown that with very high intensities you can get an electro-retinogram flicker (i.e., flicker of current from the retina) of the sort of frequency measured from the cat and other animals. That has recently been shown in Sweden. As far as the alpha rhythm goes, it seems too slow to be concerned in the subjective effects of flicker. I think that the alpha rhythm never runs much above 15 cycles per second. It is also, so far as I know, not dependent on the stimulus intensity in the same way as "just intolerable" flicker.

DR. J. W. STRANGE: I saw some colour television recently which was presented as a white screen made up of three different colours. It was interesting to observe that when the eye flicked across the screen one could see the separate colours.

I will anticipate what the authors may reply by saying that it is possible that a very sensitive subject by making a similar movement might get that sort of impression of the different colour of afterglow.

Speaking as a phosphor chemist I can say that the decay of the various lamp phosphors may be very different. One of the common phosphors—calcium silicate —has a very long red afterglow. It can be used in a "Natural" lamp with a mixture of willemite and magnesium tungstate giving green and blue emission both with short afterglows. Therefore, the net effect of a lamp coating made up of three phosphors of these types would be that the afterglow would have an appreciably different colour.

I congratulate the authors upon avoiding the error of linking decay with colour. It is a point which I have taken up with them before, and it is a relevant point. Although in practice some of the phosphors with the longest decay times are the red ones, "warm" colours and long decays are not linked; it is a purely arbitrary association. There are some blue and green phosphors which have long decay times also.

I wish to thank the authors for pointing out the possibility of progress from "just intolerable" to "just perceptible" by fairly easy steps. In other words, when the engineer provides a flicker shield or a long lag phosphor they may make all the difference between something which is just intolerable and something which is just perceptible.

The lamp engineer has a difficult problem to meet in the permissible degree of rectification in a lamp which occurs towards the end of life. This rectification is associated with uneven ageing of the two lamp cathodes. One is then emitting electrons with greater ease than the other, and you get an asymmetrical current. This normally becomes pronounced only at the end of life, and in certain circumstances a large unidirectional current may develop because the choke ceases to limit it to the designed current.

The French circuit is a very interesting one, but from a practical point of view it has one disadvantage. Our chief practical aim is to adjust the power factor and not to double the frequency of the light emission. To do the latter would cost much more and could only be achieved by ignoring the power factor. That is the only difficulty about the suggestion.

MR. R. PELERIN: I should like to ask three practical questions.

First, with regard to the wave-form of the fluorescent lamp used in the demonstration, was this a lamp with the power taken right to the end or was it with the power about a quarter of an inch free at the end?

Secondly, would the authors confirm that the demonstration fitting was on a normal 50-cycle supply and that it had two independent lamps?

Thirdly, in connection with the three-phase supply, have the authors done any researches into the problem of putting a three-phase supply into a standard three-lamp fluorescent fitting and conforming to the I.E.E. Wiring Regulations?

MR. J. R. WAKEFIELD: I was interested to hear that the multiple criterion technique had been used successfully again with flicker.

In the past when discomfort glare was under investigation, the most unpleasant situation was presented first—that is, "just intolerable"—whereas with flicker the most pleasant situation was presented first and the subject then went on to the intolerable degrees of flicker. Is there any particular adaptation reason for that?

MR. W. ROBINSON: I should like to mention an incident which interested me at the time. I met a gentleman who said that he could see the colour of the afterglow from the powder in a fluorescent lamp while it was running on 50 cycles. That is to say, he was so sensitive that he not only saw that it was flickering but could see the change of colour at the mid-cycle. I notice that the authors did not refer in any way to the question of the effect of the colour change. I wonder, first, whether in the opinion of the authors such a thing is humanly possible and, secondly, whether they have considered the question of the colour change as a part of the flicker phenomena.

MR. J. M. WALDRAM: We should recall that the problem of flicker from lamps is not new and did not start with discharge lamps. One of the first experiments I helped with nearly 30 years ago was to determine the amount of flicker from tungsten filament lamps at 25 cycles. Such circuits were in use in Glasgow at that time, and they were in use on certain parts of the Southern Railway until quite recently. One can experience considerable flicker with them.

The amount of flicker from a tungsten lamp depends upon its current more than anything else. A 1-amp lamp, referred to in the paper, normally gives comparatively little flicker, but one of lower current can give considerably more. To get the matter in its true perspective, we should remember that flicker is no new problem and that it has long existed with tungsten lamps on a.c. circuits.

I have been interested to follow the work of the French in this matter. For several years past they have been at great pains to carry out experiments with fluorescent lamps, and a summary was recently published in the Bulletin de la Société Française des Electriciens.

It started off with the premise that there was something wrong with the fluorescent lamp. Nobody knew what it was, and they have spent several years trying to find out. They thought that it might be due to ultra-violet, but they found that it was not. Then someone found something on an electro-encephalograph but it was found to be not significant. Work on glare has been carried out, but they cannot find anything specific, and recently they have been doing work on flicker, but there seems to be nothing there either.

I wonder whether it is possible that they are looking for something which is not there; at least, something which is not there in practical illuminating engineering. To say that is not in any way to decry the work which Mr. Collins and Dr. Hopkinson have been doing, because when you get a scare like this, you have to go to some trouble to lay it. I think that their work has shown us that in practical illuminating engineering we are unlikely to run into conditions where flicker will be of importance.

The values of luminance which have been quoted will be noted. The value of 10 ft.-lamberts is high for an ordinary lighted interior: 100 ft.-lamberts is very high. We have 70 lm./ft.^{2} under the ceiling in this theatre, but I doubt whether anybody has

noticed any flicker, because such a loading is nearly always split between phases and, as this paper has shown, the flicker is then greatly reduced.

MR. S. ANDERSON: I am considerably cheered by the last speaker's remarks, because I, too, have been trying to see things which were imperceptible to me.

The flicker level which Mr. Collins showed on the screen, which I gather should have been apparent to most of us in the body of the hall, was certainly not apparent to me in his "just perceptible" or even in the next lower criterion grade, and only when it fell to the third grade did it become really perceptible to me.

I wonder if I am unusually insensitive. I know from previous experience that I am moderately sensitive from a peripheral point of view, but apparently when looking straight ahead I am below average in sensitivity to flicker.

Perhaps that explains why I do not experience discomfort when at a cinema with a normal 25-frames-per-second film running. Nor do I when looking at a television screen under normal conditions, although I must admit that on some occasions when trying to get the very maximum brightness out of my set I have been conscious of flicker—I should not call it objectionable—in the peak white parts of the picture. Surely the sort of frequency range which the authors have indicated from their experiments to be that of the difference between imperceptible and intolerable is so far above the flicker frequency which we get from cinema and television screens that I am at a loss to understand this effect. I should be interested to hear the authors' explanation.

I remember many years ago being shown by one of the B.B.C. engineers their then new large studio at Broadcasting House. It was pointed out that they had adopted unusually elaborate means for avoiding stroboscopic effects. This was because of complaints that they had had from eminent orchestral conductors, that they could not tolerate the stroboscopic effect they had experienced from the bows of the violins and from their own batons.

For the new studio the B.B.C. had installed special three-phase to six-phase transformers and the fluorescent lighting was from groups of lamps on the six phases.

From the experiments which have been shown to-night, I should infer that with fluorescent lamps any elaboration of the system beyond three phases is quite unnecessary. I should be interested to know whether the authors have done any experiments on a closer phase displacement than 120 deg.

Regarding the use of three-phase supplies with a view to avoiding these flicker and stroboscopic effects, for low mounting heights it may be desirable to put the two or three lamps on different phases, or on a split-phase lead-lag arrangement in the same reflector to achieve the result. But nowadays we get many interiors—factory interiors in particular—where mounting heights of 16 ft. or more are available. Under those conditions it should be quite feasible to get an adequate reduction in stroboscopic effect by using different phases for neighbouring rows of lamps; the prevalent higher levels of illumination call for quite a close spacing of the lines of lamps.

I do not think that we should be overawed by the lack of provision for three-phase lighting circuits in existing I.E.E. Wiring Regulations. I imagine that few will have read the preface to these Regulations. This makes it clear that the Regulations are in no way intended to impede progress or developments which do not introduce a lower order of safety than that of the methods and systems which are covered by the regulations.

We should do well to remember this and not reject a new idea merely because it is not covered by existing I.E.E. or other regulations. I do not believe that the I.E.E. Wiring Regulations Committee would be unwilling to consider proposals for a future edition which might involve changes in outlook on these matters.

MR. C. R. BICKNELL: I am sure that Mr. Anderson will not mind my correcting his memory. The B.B.C. installation was certainly a six-phase one, but each phase was split for lead-lag, so that, in effect, they had 12 phases.

MR. J. G. HOLMES: I wish to make two quite simple observations. It is relatively easy to detect the colour of the afterglow from fluorescent lamp powders by holding in one's hand a piece of silvered glass or polished metal and moving it rapidly, a sort of revolving mirror technique. That might be the method adopted, consciously or unconsciously, by Mr. Robinson's friend.

The other observation is that flicker is more easily spotted and is more annoying in a non-uniform field than in a uniform luminance over the whole visual field. This comment is based on a single observation some years ago inside a large integrator, the door of which was open, and I remember that the white walls of the integrator were flickering around the door. It was a quite definite subjective effect that at the point of separation between light and dark the flicker was more pronounced.

MR. W. A. R. STOYLE: I was surprised to read the statement on the first page of the paper that the object of the study was to find why complaints of discomfort from flicker were so numerous. I have been intimately associated with discharge lamps for some 24 years, and during that period I have come across three justified complaints about flicker—an average of about one every eight years. I had almost regarded people who said that they were abnormally sensitive to flicker as being on a par with those who stated that they could see the moons of Jupiter with the naked eye.

I should like to know whether the authors have any statistical information to support the statement that complaints about flicker in America, where the common supply frequency is 60 cycles, are more numerous than in this country.

I was very interested in the demonstration of the effect of different coloured fluorescent lamps on the stroboscopic effect of flicker. In this connection it is interesting to note that there is a tendency nowadays to prefer the warmer colours of fluorescent lamps. Lamps having substantially warmer colours than some of those used in the experiments have just been introduced. I wonder whether the authors have carried out similar tests on these new lamps.

MR. H. HAZELL: I have been able to deal with complaints of eyestrain merely by changing over from "Natural" to "Warm White" coloured lamps. Do the authors think that that has something to do with the difference in afterglow? The illumination was 20 lm./ft.^{2}

MR. D. T. WAIGH (Communicated): I would like to congratulate the authors, not only on the quality of the paper, but also on their courage and foresight in raising this problem before any serious trouble has been caused by it. In view of the inevitable tendency for users to demand more and more light, at least in some applications, it is desirable that engineers should become familiar with this additional criterion of a lighting scheme or of a light source, i.e., the Flicker Index, in time to apply their knowledge of it to ensure freedom from reasonable complaint on this score.

We have carried out some tests to determine the percentage of D.C. component present in the lamp current using standard lamps and control gear. The results show that even at high field luminance the majority of lamps will cause most people no inconvenience. With a few lamps, however, D.C. components of up to 3 per cent. may occur, with the result that the just obvious level of the most sensitive subjects may be reached. Under poor operating conditions, e.g., serious over-running or poor crest factor, the discomfort range may actually be reached. A particular example of a circuit which seriously accentuates flicker is that using a resistance or incandescent lamp ballast.

On such circuits an appreciable off-period occurs each half-cycle which increases the Flicker Index.

Another point which arises is that the larger the number of lamps used to achieve the required luminance, the less is the probability of the average D.C. component of the combination becoming high enough to cause flicker of a noticeable level.

This is an argument in favour of lamps of low brightness and may provide an additional explanation of the greater incidence of flicker complaints in this country, where the standard lamp is one of "high-loading," than in the United States, where the use of "low-loading" lamps is the rule.

MR. W. HARRISON (Communicated): One of the many interesting points brought out in this paper is the rather narrow range of frequency between which the flicker sensation changes from "just perceptible" to "just intolerable," and the fortunate circumstance that the 100-cycles-per-second variation obtainable from discharge lamps on 50-cycle supply is well above the frequency which causes noticeable flicker. The authors have, however, found that some fluorescent lamps give a 50-cycle component which, when present even to the extent of a few per cent., is noticeable. The result of their examination of a large sample will be awaited with interest. We have examined on the cathode ray oscillograph the light waveform of 50 "Daylight" 80-watt lamps, but did not find any lamp giving a noticeable 50-cycle component from the middle of the lamp.

With regard to the "afterglow" of the fluorescent coating, it is a general rule for phosphors used in lamps that blue fluorescing phosphors, e.g., blue calcium halophosphate and magnesium tungstate, give no afterglow at all (i.e., 100 per cent. flicker), but as the colour of fluorescence gets "warmer" the afterglow increases until with warm white lamps the percentage flicker is about 44 per cent., and with the pink cadmium borate about 15 per cent. The percentage flicker from the phosphor above is less than this since the lamp light output includes a proportion of mercury spectrum radiation of 100 per cent. flicker.

There is little or nothing the lamp manufacturer can do in making a lamp of, say, "Daylight" colour, to reduce the flicker; he must take the phosphors as he finds them and as they follow the general rule mentioned above. However, generally, the flicker problem from fluorescent lamps, whilst appreciated, has not been regarded as a major one.

The authors refer to the reduction of flicker from installations by the use of special circuits. Here again for general application the problem of flicker has not been regarded as of primary importance and in any circuit proposed with a view to reducing flicker it is necessary to ensure that the lamps will operate at the correct current and that the circuit does not impair the life of the lamp. The three-lamp circuit from France is novel, but it appears doubtful whether it would operate on 230-volt supply.

THE AUTHORS (in reply to the discussion): Dr. Stiles and other speakers have drawn attention to the main conclusions of the paper, that flicker in fluorescent lighting is not likely to be a serious problem. It should, however, be realised from the outset that this is so only in well-engineered installations. As others have indicated, and as Mr. Waigh in his communicated contribution points out, flicker is a problem that should be dealt with before any serious trouble arises. At the moment, as Mr. Waldram claims, the levels of illumination in interiors are not such as to give rise to serious flicker, but with the inevitable increases in levels complaints of flicker will become more frequent unless steps are taken to anticipate them. The work reported in the paper was not done merely to lay a scare, necessary though that may be, but to indicate the ways in which future action should be taken.

The precise way in which the increase in field size influences the flicker sensation has not been studied. If it had been it would also have been useful to find the effect of flickering annular areas of the retina. In this way it might have been possible to find which areas of the retina were most responsible for the flicker sensation. This was not done in the present study, but it is hoped that it may be possible to initiate some further work on the problem elsewhere in which the neurological phases of the problem can be given more weight. Such work might reveal some link between the criterion of sensation and the cerebral rhythms. Considerable speculation has been entertained by French workers on the possible effects of frequencies of the light source which are multiples of the cerebral rhythms; for example, it has been suggested that as 100-cycle fluctuation is a harmonic of the alpha rhythm at 12½ c.p.s. resonance effects may occur in the brain even though no visal sensation of flicker results. We have not concerned ourselves with such speculations although we have studied the relevant experimental work carefully.

We also do not feel that the Flicker Index is the last word, but it is a convenient and often reliable guide to the effects of different types of waveform. A detailed harmonic analysis of the various waveforms would be valuable but was outside the scope of the present study.

Dr. Stiles is going far beyond the actual terms of reference of the multiple criterion method in his contribution. One of the essential features of the technique as developed by one of us (Hopkinson, Trans. I.E.S. (London), **5,** 25, 1940, and Q. J. Exp. Psychol., **2,** 124, 1950) is that only a limited series of criteria is used, regular repetitions are necessary and borderline criteria are employed. Only in this way can the reliability on which Dr. Stiles congratulates us be achieved. He has himself introduced similar precautions into his threshold judgments. Without such care, judgments in either type of experiment would be much less reliable.

We agree with Dr. Tansley that the higher frequencies of observable flicker which our studies show are due to the much larger field size. This is confirmed by Bouma's work among others and this may also account for the wider variation. Our observers were not selected in the way that Lythgoe and Tansley's were, however, and this may also be a factor. Some of our observers showed much less variance than others and these would have been picked out had we been making a study in which observer variance was a disadvantage. Pre-adaptation might also be a factor. Naturally we wanted our observers in a state not too far removed from normal everyday conditions. Clearly much work remains to be done on flicker adaptation and on interaction effects. The contrast effect mentioned by Mr. Holmes, and the effects of adjacent areas mentioned by Dr. Stiles, must be due to the effect which stimulated receptors in the retina have on the adjacent unstimulated ones. The "contrast grading" effect in glare (Petherbridge and Hopkinson, Trans. I.E.S. (London), **15,** 39, 1950) must in the same way have its origin here.

With regard to Dr. Strange's remarks on the permissible degrees of the rectification effect, the results in the paper give an indication that this should not be more than about 5 per cent. at a luminance level of 10 ft.-lamberts and 1.5 per cent. at 50 ft.-lamberts, but further study is perhaps needed. It is interesting that Mr. Waigh has found D.C. components which correspond to the order of value of rectification which we have found, whereas Mr. Harrison has not. We hope that it may be possible to make comparable measurements on the same lamps in order to find out how much of the effect is due to the lamp and how much to the running conditions. Mr. Waigh's contribution is especially valuable in that he points out other conditions in which flicker may occur, conditions which we ourselves have not studied. We endorse his view that low-loading lamps should be advocated for high luminance installations. In addition to the various advantages which such lamps have from the flicker point of view, they are also less liable to cause glare.

Mr. Harrison points out that in practice, "warm colour" lamps generally have more afterglow but, as Dr. Strange shows, this is fortuitous and not an invariable rule. It would however be useful if a "Daylight" lamp with a low Flicker Index could be produced, because such lamps are often used to give very high levels of luminance, e.g., in drawing offices where a satisfactory blend with daylight is needed.

Mr. Stoyle, Mr. Anderson, and Mr. Waldram have each given their reasons for their views that flicker is unimportant. Mr. Anderson certainly must be relatively insensitive, because the demonstrations appeared to work for people in most parts of the hall. Responsible firms of lighting engineers take great care to ensure that their installations are well-engineered; in such cases many complaints of flicker would not be expected. Our remarks on the frequency of complaints here and in the United States are based on discussions with engineers with experience of both. As far as we know there are no statistics. In reply to Mr. Stoyle, we have not studied any of the new "de-luxe" types of lamp, but would like to do so In reply to Mr. Anderson, a television or cinema screen fills only a small part of the visual field at a low level of luminance, with the result that the retinal illumination is low and the threshold of flicker perception is of low frequency, i.e., well below the 48, 50, or 72 c.p.s. fluctuation of the normal cinema or television picture. Personal experience demonstates forcibly that when the luminance of a television screen is raised to a high level complaints of flicker are immediate.

In reply to Mr. Wakefield, we ran the experiment the way we did for the same reason that we did the glare experiment the other way, that is, because we wanted to work *with* rather than *against* the adaptation mechanism of the eye. The eye becomes conditioned to flicker in a complex way. This was in fact studied, although the results are not included in the paper; we hope to publish these results elsewhere.

In reply to Mr. Anderson and Mr. Bicknell, the "flicker" effect on a rapidly moving baton or bow can be very annoying in fluorescent lighting and we are not surprised at the complaint. The same trouble was experienced in a Swedish school where, apart from this, the lighting was well liked. Three-phase working should have cured the trouble, because this gives less flicker than normal filament lamps.

With regard to high mounting of fittings and the spreading of the fittings among the phases, as compared to taking the three phases into one fitting, some full-scale tests might well be done. It is useful to note from Mr. Anderson that the I.E.E. Regulations can be adjusted to cope with progress in lighting technique. This answers Mr. Pelerin's point. In a large room with a high degree in inter-reflection of light, it should not be necessary to take three phases into each fitting.

In reply to Mr. Pelerin and others who were concerned about the lamps demonstrated at the lecture, these were not working on a normal supply. We deliberately introduced a rectifier into the circuit to produce a large 50-cycle component otherwise people at the back of the hall would not have seen any flicker owing to the small angular subtense of the demonstration to them. Mr. Robinson's questions have been answered by other contributors. We have not met an observer as sensitive as Mr. Robinson's friend.

In reply to Mr. Hazell, the greater comfort on changing from "Natural" to "Warm White" lamps is rather surprising. The change goes the right way according to our results, but we should not have expected it to be so marked.

Finally, Mr. Waldram has rightly drawn attention to the levels of luminance and the "observer-occasion" probabilities which we have given in the paper, and reiterated our conclusion that flicker in fluorescent lighting is not likely to be serious. That is not the same thing as to say, as Mr. Waldram does, that flicker is "something which is not there in practical illuminating engineering." Perhaps Mr. Waldram has missed the significance of the concept of "observer-occasions." If the sensitive observer, who accounts for a large number of such occasions, does not complain, or is not a person

of any importance, his " observer-occasions " will pass unconsidered. If he is an executive who is used to having matters to his own satisfaction, he may refuse to have fluorescent lighting installed in the premises under his control. This is the situation which lighting engineers should watch. It is not one to which we could give any attention in the paper, which is based on factual experimental findings, but it is a psychological factor which may become more significant as luminance levels in interiors are raised in accordance with modern ideas on visual efficiency.

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